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EFFECT OF DRAINAGE AREA ON HYPSOMETRY FROM AN ANALYSIS OF SMALL-SCALE DRAINAGE BASINS IN THE SIWALIK HILLS (CENTRAL NEPAL)

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ABSTRACT

Hypsometry of drainage basins (area–elevation analysis) has generally been used to infer the stage of geomorphic development and to study the influence of varying forcing factors (i.e. tectonics, climate, lithology) on topography. However, the scale dependence of hypsometry has generally been neglected. In order to assess the scale dependence of hypsometry, this study focuses on the sensitivity of hypsometry to different Digital Elevation Model (DEM) resolutions and on the influence of drainage area. Hypsometry inferred from different DEMs is shown to be robust against variations of their resolution. However, hypsometry appears to be dependent on drainage area. We propose that this scale dependence may reflect the varying importance of river and hillslope processes with basin area. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: hypsometry; drainage basin; river processes; hillslope processes; tectonic uplift

INTRODUCTION

Since the Earth's surface is shaped by concurrent tectonics and erosional processes, the analysis of processes involved in landscape building requires pertinent geomorphic parameters. Weissel *et al.* (1994) suggest that hypsometry may reflect the interaction between tectonics and erosion and could provide a valuable geomorphic index in order to constrain the relative importance of these processes. Hypsometry is the relative proportion of area at different elevations within a region. The hypsometric curve represents the relative proportion of basin area below (or above) a given height (Strahler, 1952). This surface elevation distribution is commonly used (e.g. Harrison *et al.*, 1983; Rosenblatt and Pinet, 1994) for topographic comparisons because it gives three-dimensional information for a two-dimensional approach. The integral of this curve with respect to relative height provides a simple morphological index of the elevation distribution within the area considered (Ohmori, 1993). However, this parameter is ambiguous since areas with different types of hypsometric curve can yield the same hypsometric integral value.

Hypsometry has been generally used to infer the stage of geomorphic development (Strahler, 1952). From an analysis of numerous small-scale drainage basins (about a few square kilometres in area), Strahler (1952) has shown that (1) a convex shaped hypsometric curve characterizes basins in the stage of youth, (2) an S-shaped hypsometric curve (concave upwards at high elevations and concave downwards at low elevations) characterizes basins in the stage of maturity, and (3) a concave hypsometric curve characterizes basins in the peneplain stage. However, by combining an analysis of large-scale natural drainage basins in Japan (up to 10 000 km^2) and a study of simulated basins based on empirical laws deduced from Japanese mountains, it has been shown that hypsometric curves are either concave or S-shaped, where basins are at equilibrium, but are never convex. Willgoose (1994) has used a numerical approach to investigate the topographic evolution

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of a basin through the calculation of the continuity equations for runoff and erosional processes. This author has shown that in the case of declining equilibrium (the basin is initially uplifted and then evolves only through erosional processes) simulated basins reach a constant form. In all simulated cases, computed for a range of parameter values, the hypsometry converges to a constant S-shaped curve. This is not consistent with the concave hypsometric curve proposed by Strahler (1952) for basins at the peneplain stage. These discrepancies may result from controlling parameters such as climate, lithology and tectonics which may also influence the hypsometric curve. For example, Masek *et al.* (1994) have proposed a climatological effect on the hypsometry by comparing two large-scale drainage basins in the central Andean plateau. Indeed, the climate differs strikingly between the two regions studied (the Beni region experiences monsoonal precipitation while the Pilcomayo region is semi-arid), whereas there is no evidence for a major change in lithology or tectonic context. Subsequently, variations in hypsometry are likely to reflect the difference in erosional processes driven by climate. In a study of San Gabriel Mountains, California, Lifton and Chase (1992) have calculated the hypsometry within square windows where the relative tectonic activity and the rock erodibility were quantified. These authors suggested the influence of tectonic activity on the hypsometric integral at large scales (1000 km^2) and a stronger influence of lithology at small scales (100 km^2). They also tested the influence of varying uplift rates on hypsometry, from a numerical model of landscaping, showing that the hypsometric integral was positively correlated to the uplift rate. This result contrasts with the negative correlation found in the natural landscape. As these authors pointed out, this discrepancy may be due to variations in rock erodibility and to the complex tectonic patterns in the San Gabriel Mountains that are not accounted for in their numerical simulation. In a comparative study of basins sampled in the same tectonic context of the southern border of the French Massif-Central, it has been shown that lithology is the dominant control on the hypsometric curve (Hurtrez and Lucazeau, in press). Where rocks are resistant to erosional processes (such as massive limestones, granites or volcanics), hypsometry is characterized by a large proportion of area at high elevation. Where rock resistance is low (e.g. schists, marls, unconsolidated sandstones), hypsometry is characterized by a large proportion of areas at low elevation. In order to investigate the influence of drainage basin geometry (drainage area and aspect ratio) on hypsometry, Willgoose and Hancock (1998) used a numerical model (SIBERIA) for simulating landscape evolution. This study showed a conspicuous effect of basin geometry on hypsometry. This result was confirmed by a comparison with rainfall-erosion simulation experiments.

This review shows that hypsometry could be sensitive to various forcing factors such as tectonics, lithology and climate. Numerical and experimental modelling further shows the dependence of hypsometry on basin geometry. However, the scale dependence of hypsometry and particularly the influence of drainage area have generally been neglected in natural settings. Here, we report a study of the scale dependence of hypsometry calculated within drainage basin limits from Digital Elevation Models (DEMs). First, we investigate the sensitivity of hypsometry to different resolution DEMs and then we assess the influence of varying drainage area on hypsometry.

METHOD

Study area

The study area lies on Siwalik Hills in central Nepal (Figure 1). This study area was chosen because of its well constrained climatic, lithologic and tectonic conditions (see Hurtrez *et al.*, in press; Lavé, 1997). Elevations range from 250 to 2000 m. At the scale of investigation, it was assumed that the relative importance of geomorphic processes does not change significantly with elevation.

Due to the monsoonal regime, the Siwalik Hills are affected by an extremely humid and hot climate that can be considered to be uniform at the scale of investigation. Annual mean temperature is of the order of 22°C. About 70 per cent of the >2000 mm a^{-1} annual precipitation falls within three months.

The bedrock consists of Tertiary molasses that have been eroded from the Himalaya and accumulated over the Indian basement since the Middle Miocene (e.g. Harrison *et al.*, 1993). Three lithostratigraphic units are

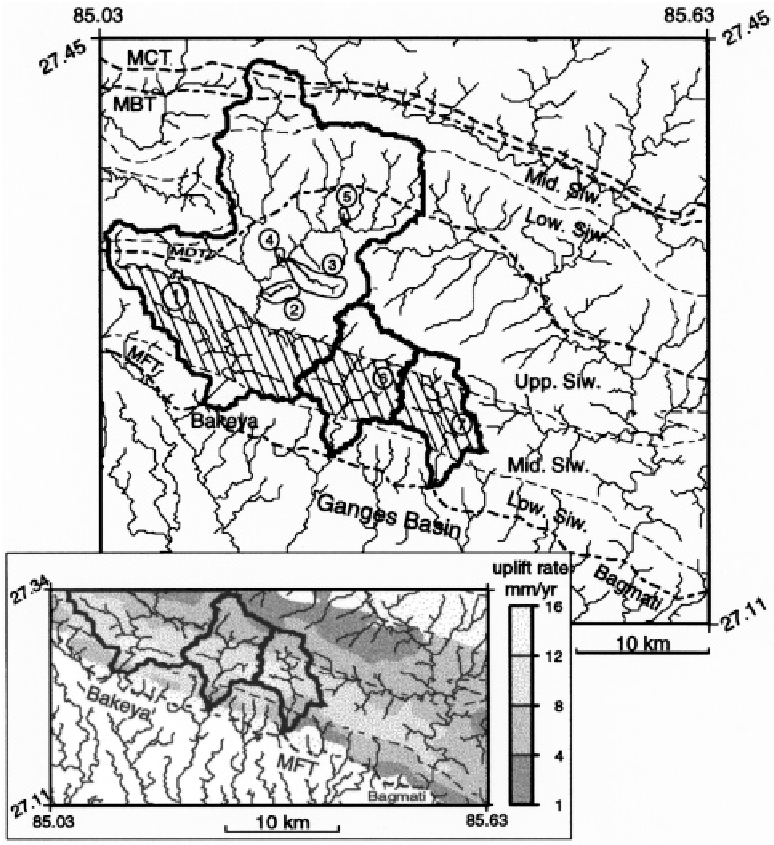

Figure 1. Simplified structural map of the study area, in the Siwalik Hills, between the Bakeya and Bagmati rivers. Key: thin black lines, channel networks; thin dashed lines, lithologic limits; Low. Siw., Lower Siwalik; Mid. Siw., Middle Siwalik; Upp. Siw., Upper Siwalik; heavy dashed lines, main thrusts; MFT, Main Frontal Thrust; MDT, Main Dun Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; heavy black lines: limits of basins 1 (Bakeya), 6 and 7; hatched area, zone where the calculation of hypsometry is restricted for basins 1, 6 and 7. Inset map: uplift rate deduced from bedding dip measurements, assuming a fault-bend fold geometry and parallelism with the dip of the ramp

generally distinguished, the Lower, Middle (fine-grained sandstones and mudstones) and the Upper Siwalik (conglomerates).

The Siwalik units are presently being thrust over the recent alluvial sediments of the Ganges foreland basin, along the Main Frontal Thrust (MFT) (Figure 1). The Siwalik units have been deformed by thin-skinned tectonics induced by underthrusting of the Indian basement beneath the Lesser Himalaya (Delcaillau *et al.*, 1987). Structural sections across the study area reveal a simple anticline structure (fault-bend fold) related to a 25–50° northward dipping ramp, rooting into a horizontal *décollement* at the base of the 5–6 km thick Siwalik group (Lavé and Avouac, submitted). A detailed analysis of four levels of folded fluvial terraces (strath terraces) allowed us to validate the fault-bend fold model (Lavé and Avouac, submitted). According to such a kinematic model, the tectonic rock uplift, *U*, is proportional to the horizontal shortening rate, *V*, across the fold:

$$U = V \times \sin(\alpha)$$

where α is the dip of the beds, assuming parallelism with the dip of the ramp.

This tectonic model was used to derive uplift rate from the shortening rate (deduced from folded strath terrace profiles) and the bedding dips measured in the study area (Figure 1).

Table I. Drainage area and hypsometric integral of the basin 1, calculated from different resolution DEMs

MNT		Basin 1	
Origin	Resolution (m)	Area (km^2)	Hypsometric integral
SPOT	20	322·0	0·190
SPOT (sampling)	40	321·8	0·190
SPOT (sampling)	100	323·7	0·190
SPOT (sampling)	200	324·4	0·196
SPOT (averaging)	200	324·2	0·197
SPOT (averaging)	400	328·2	0·199
SPOT (averaging)	800	387·2	0·205
DCW	825 × 925	323·0	0·217

Topographic data sets

A high resolution DEM calculated by a pair of SPOT images (photogrammetry) and projected over a Universal Transverse Mercator (zone 45) grid as a Cartesian reference frame provides a horizontal resolution of 20 m. The resolution of this DEM is degraded by sampling and by averaging to provide different horizontal resolution DEMs, ranging from 40 m to 800 m (Table I). In addition, the *Digital Chart of the World* (DCW) database (Defence Mapping Agency, 1992) at the resolution of 30 arc-seconds (roughly 825 m × 925 m, in the study area) is used to compare hypsometry calculated from databases of different origins.

Basin limits and channel network

Hypsometry is defined within drainage basin limits (Strahler, 1952). A drainage basin is defined as the set of cells related by their flow pathway to the basin outlet. This requires the extraction of the channel network from DEMs. For this, the software 'MAD' (Moussa, *et al.* 1997) was used. This software is based on the standard methods described in Band (1986). A single flow drainage direction, following the steepest downward slope, is calculated for each cell of the grid. Sinks are filled, given a user-supplied threshold area, to ensure the continuity of drainage. The channel network is extracted according to a constant threshold contributing area. After drainage basin limit determination, according to the previous method, hypsometric curve and hypsometric integral have been calculated with the non-corrected elevation database.

The drainage basin of the Bakeya river (Figure 1; basin 1) is selected in order to investigate the sensitivity of hypsometry to DEMs of different origins and with different resolutions. This basin is chosen because its size (about 300 km^2) allows hypsometric analyses to be performed from DEMs with resolution ranging between 20 and 800 m.

In order to assess the influence of drainage area on hypsometry, three comparative studies were undertaken. First, four basins with varying drainage area (from 1·7 km^2 to 10·5 km^2) were selected in Upper Siwalik (Figure 1; basins 2, 3, 4 and 5). All overlie unconsolidated conglomerates with similar lithologic, climatic and tectonic conditions. Elevations are within the same range, from 250 m to 550 m. Second, for the same basin (basin 3), three sub-basins were defined with decreasing drainage area (Table. II; basins 3a, 3b and 3c). The outlets of these different sub-basins were defined along the mainstream. Third, three basins with varying drainage area (from 36 km^2 to 324 km^2) were selected within the fault-bend fold related to the Main Frontal Thrust (MFT) (Figure 1; basins 1, 6 and 7). In order to compare hypsometry within areas characterized by homogeneous climatological and lithological conditions and particularly rapid uplift rate, the calculation of hypsometry of the three basins is restricted to a zone overlying the Middle Siwalik rocks (hatched areas in Figure 1).

Calculating hypsometric curve and hypsometric integral

The hypsometric curve represents the relative proportion of a basin area that lies below a given height (Strahler, 1952). For a selected basin, the range of elevations is divided into equal elevation intervals. For each interval the proportion of basin area is calculated. Elevations are normalized by the relief of the

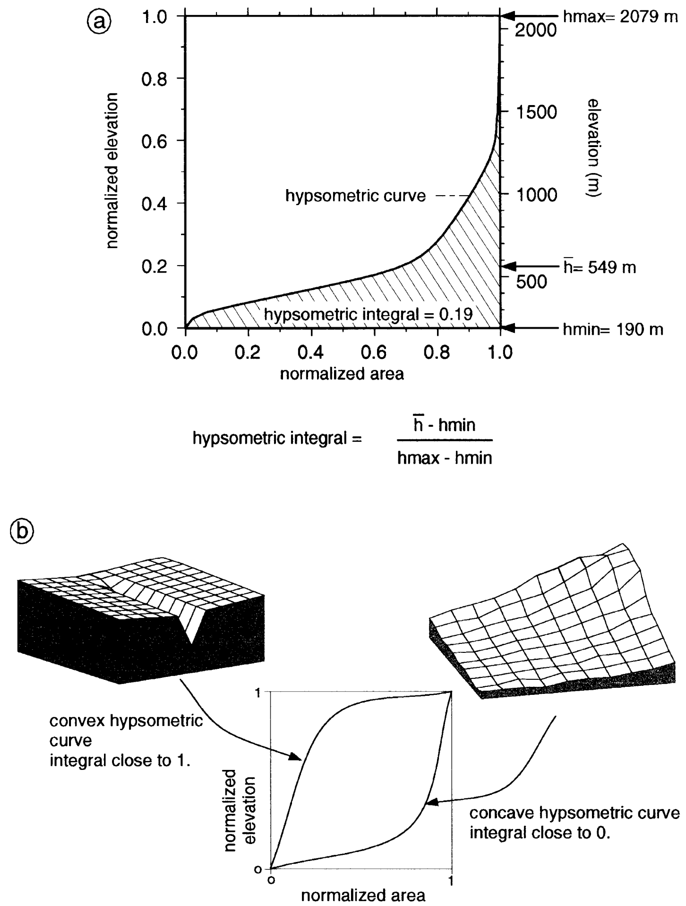

Figure 2. (a) Hypsometric curve and hypsometric integral of the Bakeya basin, calculated with the 20 m resolution DEM. (b) Relationship between basin morphology and hypsometric curve

Table II. Drainage area and hypsometric integral of selected basins

Basin number	Bedrock	Drainage area (km^2)	Hypsometric integral
2	US	5·2	0·41
3	US	10·5	0·45
3a	US	6·5	0·42
3b	US	2·5	0·45
3c	US	0·8	0·53
4	US	1·8	0·56
5	US	1·7	0·56
1	MS	323·7	0·34
6	MS	47·6	0·39
7	MS	36·5	0·43

US, Upper Siwalik; MS, Middle Siwalik

catchment so that they range from 0 to 1·0. The hypsometric integral represents the area under the hypsometric curve. The hypsometric integral (*Int*) equals (Figure 2):

$$Int = \frac{\overline{alt} - altmin}{altmax - altmin} \tag{1}$$

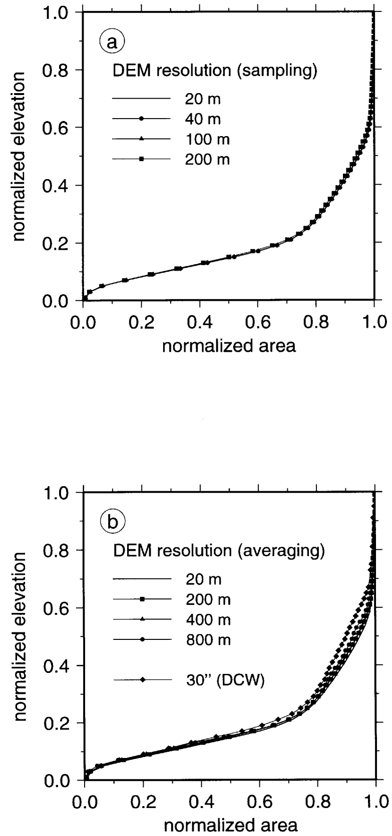

Figure 3. (a) Hypsometric curves calculated for basin 1 with different resolution DEMs. The nominal resolution (20 m) is degraded by sampling (●, 40 m; ▲, 100 m; ■, 200 m). The superposition of the different curves shows that hypsometry is independent of DEM resolution. (b) Hypsometric curves calculated for basin 1 with different resolution DEMs. The nominal resolution (20 m) is degraded by averaging (■, 200 m; ▲, 400 m; ●, 800 m). ◆, DCW DEM with 30 arc-seconds resolution

where $\overline{alt}$ is the mean elevation of the basin, *altmin* and *altmax* are minimum and maximum elevations within the basin, respectively.

Hypsometric curves have the potential to distinguish landscapes characterized by different shapes (Figure 2). It also seems possible to retrieve the relative importance of slope processes versus river processes from the hypsometric curve (Willgoose and Hancock, 1998). Since the relative importance of fluvial processes increases with drainage area, the drainage area may exert a significant control on hypsometry where the uplift rate is low or where the variations of drainage area are very important.

RESULTS

DEM resolution

The results (Figure 3a, 3b and Table I) show that the hypsometry of a basin is a geomorphic parameter which is robust against varying DEM resolution. The most important, but still moderate, difference arises from the comparison of hypsometric curves calculated from DEMs of different origins (SPOT and DCW, Figure 3b). This shows that, in spite of the coarse resolution of the DCW DEM with respect to the drainage area (about 300 km^2), the hypsometric analysis inferred from this DEM provides a correct elevation distribution function.

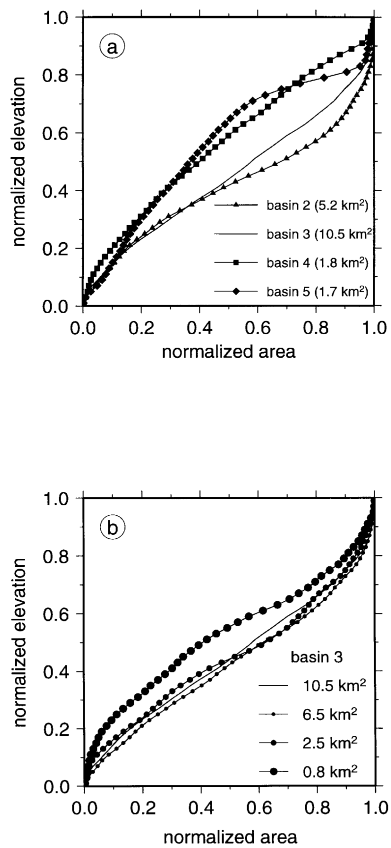

Figure 4. (a) Hypsometric curves calculated for four different basins lying on unconsolidated conglomerates (Upper Siwalik) with similar lithologic, climatic and tectonic conditions. (b) Hypsometric curves calculated for basin 3 and three sub-basins with decreasing drainage area

Drainage area

Where the uplift rate is low, related to the shallowing of the ramp of the MFT, the comparison of hypsometric curves of the basins 2, 3, 4 and 5 shows that their hypsometries are significantly different (Figure 4a, Table II). Hypsometric curves are either convex for the smaller basins (basins 4 and 5), or S-shaped for the larger ones (basins 2 and 3). In addition, within the same basin, the evolution of the hypsometric curve with basin area shows that the proportion of basin area at low elevations decreases with increasing area (Figure 4b, Table II). This suggests that a relationship might exist between hypsometry and drainage area.

Where the uplift rate is rapid within the fault-bend fold, related to the steepening of the ramp of the MFT, the results show that hypsometric curves are similarly S-shaped for the three selected basins (1, 6 and 7; Figure 5a). However, at low elevations, relative proportions of basin area differ significantly. About 25 per cent of basin 1 lies below the first 20 per cent of elevation range while this proportion is about 16 per cent for basin 6 and only 7 per cent for basin 7. This result supports the scale dependence of hypsometry and confirms previous results.

DISCUSSION

Hypsometry has been widely used for topographic analyses and has been shown to be sensitive to different forcing factors in landscape building. However, the scale dependence of hypsometry has generally been neglected in previous studies. The results indicate that hypsometry is robust against varying DEM resolution.

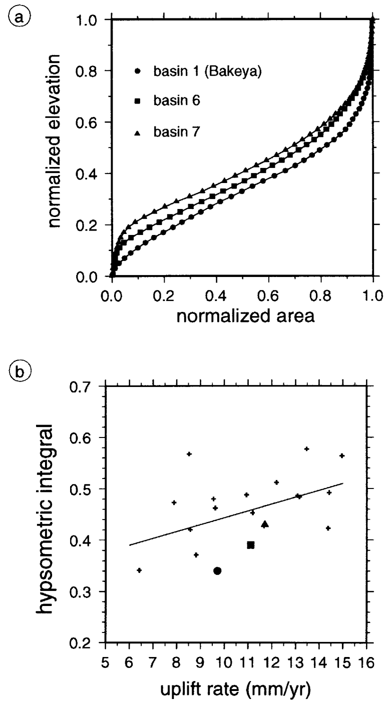

Figure 5. (a) Hypsometric curves calculated for three different basins (1, 6 and 7) in the area overlying the Middle Siwalik rocks, within the fault-bend fold related to the Main Frontal Thrust. ●, basin 1; ■, basin 6; ▲, basin 7. (b) Plot of the hypsometric integral versus mean uplift rate. Crosses: 17 basins selected between Bakeya and Bagmati rivers, within the fault bend fold related to the Main Frontal Thrust. ●, basin 1; ■, basin 6; ▲, basin 7

This property suggests: (1) that hypsometry is valuable for geomorphic analysis; and (2) that comparisons of hypsometry calculated from different resolution DEMs are reliable (Rosenblatt and Pinet, 1994). However, the scale dependence shown in two different structural contexts, and within basins of different sizes, suggests that hypsometry is not independent of the basin characteristics in a given region. At least two non-exclusive hypotheses may explain the varying pattern of hypsometry for basins selected where the forcing factors are similar. (1) Although it has been assumed that forcing factors are homogeneous within the selected basins, a variation of one of these factors, not tractable in this study, might explain the variation in hypsometry; (2) The scale dependence of hypsometry may reflect the varying importance of river and hillslope processes with basin area. Where the drainage area is small, hillslope processes would be dominant. In that case the hypsometric curve would be convex with a hypsometric integral close to 1 (Figure 2). Conversely, with increasing drainage area, the importance of river processes would increase; the hypsometric curve would become concave with a hypsometric integral close to 0 (Figure 2).

In order to investigate the relative importance of drainage area and tectonic uplift on hypsometry, the hypsometric integral versus the mean uplift rate for different basins, were compared (Figure 5b). In a previous study (Hurtrez *et al.*, in press), 17 drainage basins experiencing similar lithologic, climatic and base-level conditions were selected between the Bakeya and Bagmati rivers, within the fault-bend fold. These basins are characterized by varying drainage area (1·3–20·1 km^2) and varying mean uplift rate (6·4–15·0 mm^{-1}, Table III). A linear correlation analysis shows that the hypsometric integral is independent of drainage area: $r = -0{\cdot}11$ (non-significant). However, hypsometric integral is significantly correlated to the uplift rate ($r = 0{\cdot}49$, $p < 0{\cdot}05$; Figure 5b). This suggests that in the Siwalik Hills, in regions submitted to rapid tectonic uplift rates, tectonic control is dominant on drainage basin hypsometry. However, when variations of

Table III. Drainage area, mean uplift rate and hypsometric integral of 17 basins overlying Lower and Middle Siwalik rocks, within the fault-bend fold related to the Main Frontal Thrust, between Bakeya and Bagmati rivers. Hypsometric integrals were calculated from a 20 m resolution DEM

	Basin area (km^2)	Uplift rate ($mm\ a^{-1}$)	Hypsometric integral
1	2·77	8·81	0·371
2	1·26	14·95	0·564
3	2·56	12·19	0·512
4	20·13	9·61	0·462
5	8·35	13·08	0·486
6	1·37	13·47	0·577
7	2·68	8·51	0·567
8	2·96	11·19	0·453
9	2·55	14·37	0·423
10	5·05	14·41	0·492
11	5·73	11·67	0·427
12	2·03	10·94	0·488
13	8·72	13·16	0·484
14	7·21	7·87	0·473
15	3·64	6·41	0·341
16	3·26	8·57	0·420
17	7·41	9·54	0·480

drainage area are more important (basins 1, 6 and 7; Figure 5b), the discrepancy with the previous relationship between uplift rate and hypsometric integral increases with drainage area. This suggests that, in the study area, where variations of drainage area are important, the drainage area may exert a stronger influence on hypsometry than the uplift rate.

The scale dependence of hypsometry on basin area shown in a natural setting confirms previous conclusions drawn by Willgoose and Hancock (1998) with numerical and experimental modelling of basin evolution. Therefore, the hypsometric curve cannot be used as a proxy of landscape evolution stage as proposed by Strahler (1952).

The scale dependence shown in this study is consistent with a joint influence of river and hillslope processes on landforms, as shown by Willgoose and Hancock (1998), for numerical modelling, and as suggested by Deschaux and Souriau (1996) for large-scale basins. For large basins (area of the order of 100 000 km^2), Deschaux and Souriau (1996) approximated the basin shape by a rectangle. Therefore, the hypsometric curve (normalized elevation versus normalized area) was indentified to the corresponding hypsometric profile (normalized elevation versus normalized distance along the main river). Deschaux and Souriau (1996) showed that the hypsometric profile and the normalized main river profile (normalized elevation versus the normalized distance along the main river) followed logarithmic profiles, and the ratio between the hypsometric profile and the main river profile was constant, unless at basin outlet. This result suggested that the slope of the hillslopes is not independent of the slope of the main river, consistent with the coupling between river processes and hillslopes processes. Therefore, this method could be valuable in assessing the relative importance of river processes versus hillslopes processes; however, it is restricted to large-scale basins, since the hypsometric curve cannot be accounted for by a simple logarithmic profile for small-scale basins.

The scale dependence of hypsometry supports the hypothesis that this geomorphic parameter is very sensitive to the processes involved in landscaping, as suggested by Weissel *et al.* (1994). Forcing factors that control elevations within a basin (such as tectonics), erosional processes (such as climate and drainage area) and the coupling between river processes and hillslope processes (such as lithology) are tractable through hypsometric analysis. However, careful analyses are required to ascribe variations of hypsometry to one of these factors.

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